Photometric Abundances for G-Dwarfs: A Cautionary Tale

Bruce A. Twarog, Barbara J. Anthony-Twarog, and Delora Tanner
Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045-2151
Electronic mail: twarog@ukans.edu,bjat@ukans.edu,dtanner@ku.edu

ABSTRACT

Analysis of cluster and field star *uvby* data demonstrates the existence of a previously undetected discrepancy in a widely used photometric metallicity calibration for G dwarfs. The discrepancy is systematic and strongly color-dependent, reducing the estimated [Fe/H] for stars above [Fe/H] ~ -0.2 by between +0.1 and +0.4 dex, and creating a deficit of metal-rich stars among dwarfs of mid-G and later spectral type. The source of the problem, triggered for stars with $b - y$ greater than about 0.47, appears to be an enhanced metallicity dependence for the c_1 index that increases as temperature declines. The link between c_1, normally a surface gravity indicator, and metallicity produces two secondary effects. The deficit in the photometric abundance for a cool dwarf is partially compensated by some degree of evolution off the main sequence and cool dwarfs with metallicities significantly above the Hyades are found to have c_1 indices that classify them as giants. The potential impact of the problem on stellar population studies is discussed.

Subject headings: stars: abundances — techniques: photometric

1. INTRODUCTION

The *Hipparcos* (Perryman et al. 1997) era in stellar astronomy has produced a revolution in our ability to define the evolutionary state of large numbers of stars in a wide array of stellar classes and subclasses. The capability exists to define reliably the distance and tangential velocity of thousands of stars and place them, with a high degree of accuracy, at the appropriate location in some form of color-magnitude diagram (CMD). The translation of the CMD location into a point on an evolutionary track for a star of a given mass requires information external to the *Hipparcos* survey, in particular, the conversion between the observational and the theoretical plane that depends, in part, on the metallicity of the star.

This quantum leap in the quality and quantity of data supplied by *Hipparcos* has generated a tremendous gap between analyses based on these data as opposed to the more traditional, ground-based observations. A prime example is presented by stellar spectroscopy. Though low-resolution spectroscopic catalogs such as the *Michigan Catalog* (Houk & Cowley 1975; Houk 1978, 1982; Houk & Smith-Moore 1988; Houk & Swift 1999) compare favorably to the space-based sample in number, high-resolution, spectroscopic catalogs listing abundances, e.g. Cayrel de Strobel et al. (2001), contain only a few thousand stars of mixed range and reliability. In the absence of a spectroscopic equivalent of *Hipparcos*, investigators have used a variety of approaches to fill the void, the most common being analysis of photometric indices. Of the many photometric systems available, arguably the most valuable and most used for large-scale studies is the Strömgren *uvby* system. The intermediate-band filters of the system have been selected to disentangle the overlapping effects of varying temperature, metallicity, and surface gravity and, over the last 35 years, the indices have been calibrated to supply information on stars over the entire range in temperature, luminosity, and abundance. Moreover, the photometric sample numbers over 60,000 stars and is currently available on a uniform system via the efforts of Hauck & Mermilliod (1998). Though

composite catalogs can often be of questionable value due to the inadequate nature of the transformations among different observers, the catalog of Hauck & Mermilliod (1998) is dominated by the extraordinary sample collected over the last 20 years by Olsen (1983, 1984, 1993, 1994) and others (e.g., Schuster & Nissen 1988; Schuster et al. 1993), often using the same instrumentation and reduction procedures. Thus, the transformation corrections among the various published catalogs are small to negligible.

For stellar population investigations of the solar neighborhood, *uvby* photometry has long been a mainstay, with an emphasis on stars of spectral type A through early G. Because the c_1 index supplies a measure of M_V, it permits a determination of the location of the star in the CMD and, in combination with the metallicity via m_1 and temperature via $b-y$ or Hβ, an age through comparison with appropriate isochrones (Twarog 1980; Meusinger et al. 1991). With the availability of *Hipparcos* parallaxes to determine M_V, the role of the *uvby* system has shifted to one of supplying internally consistent abundances, while the spectral range of interest has moved redder, to stars of type late G and early K. A few of the recent examples of the use of the system may be found in Laughlin (2000); Rocha-Pinto et al. (2000); Haywood (2001); Feltzing et al. (2001); Reid (2002). As invariably happens when new data open up previously unexplored avenues of research, the analyses lead to contradictions with earlier work and with each other; examination of the citations noted above prove that the *Hipparcos* data analyses are no exception. In evaluating such contradictory evidence, it is crucial to isolate the real effects of galactic and stellar evolution from the artifacts of the technique. The purpose of this paper is not to review the strengths and weaknesses of the many recent solar neighborhood investigations tied to *uvby* photometry. Our purpose is to highlight an inherent problem in the *uvby* metallicity calibration for disk G and K stars, a calibration that is being used with increasing frequency in such studies.

In Sec. 2, we will present the evidence that a problem does, in fact, exist. In Sec. 3, we track down the source of the discrepancy, while investigating its role in population studies in Sec. 4. Sec. 5 provides a summary of our conclusions.

2. The Problem

Over the last 15 years, we have been involved in the development of a photometric system known as *Caby* photometry. The *Caby* system represents an extension of the traditional four-color, *uvby* intermediate-band photometric system to a fifth filter centered on the H and K lines of Ca II. Details of the filter definition and design as well as the fundamental standards may be found in Anthony-Twarog et al. (1991) while an extensive catalog of stars observed on the system and tied to the $b-y$ scale of Olsen (1993) may be found in Twarog & Anthony-Twarog (1995). The filter was designed initially with metal-deficient stars in mind, as demonstrated by numerous applications to date on normal field stars (Anthony-Twarog et al. 1991, 1992; Anthony-Twarog & Twarog 1998; Anthony-Twarog et al. 2000), clusters (Anthony-Twarog et al. 1995; Rey et al. 2000), and variables (Baird 1996; Hintz et al. 1998). Metallicity calibrations have been produced for both the metal-deficient giants (Anthony-Twarog & Twarog 1998) and metal-deficient dwarfs (Anthony-Twarog et al. 2000), but preliminary analysis indicated that for dwarfs hotter than the sun, the *hk* index, defined as *(Ca-b)-(b-y)*, remains metallicity sensitive for stars of solar abundance or higher (Twarog & Anthony-Twarog 1995), a result consistent with the theoretical models of Soon et al. (1993). Because of the high metallicity of the Hyades relative to the typical star in the field of the solar neighborhood, observations of this cluster were obtained along with the field stars as a means of testing this prediction.

In the course of analyzing a sample of over 100 Hyades dwarfs extending to spectral type of late K, it was noted that the cooler dwarfs in the Hyades occupied an unexpected location in the *hk, b-y* diagram. The data imply that higher metallicity shifts the Hyades relation to *lower hk* at a given $b-y$ relative to the average disk star, i.e., the Hyades stars formed an *upper* bound in the figure rather than a lower bound (Anthony-Twarog et al. 2002). As a test of the metallicity option, the stars located above the Hyades in the two-color relation were identified and a check made for any published abundance information, photometric or spectroscopic. In the course of this search, it became apparent that a serious deficiency of stars with solar

metallicity or higher exists among the cool stars in the published *uvby* catalogs. The source of this problem emerged when we attempted a differential comparison of the photometric indices of the stars directly with those of the Hyades dwarfs of the *uvbyCa* system.

To illustrate the problem, we make use of the *uvby* data for two clusters, Hyades and Praesepe, with abundances above solar as measured via spectroscopy (e.g., Boesgaard 1989; Friel & Boesgaard 1992) and photometry (e.g., Nissen 1988; Twarog et al. 1997)). The *uvby* photometric data for the Hyades come from Olsen (1993, 1994) while those of Praesepe come from Reglero & Fabregat (1991). Comparison of 16 stars common to Olsen (1993, 1994) and Reglero et al. (1992) for the Hyades produced modest offsets between the two photometric systems. The average differences among the various indices, in the sense (OLS - REG), are +0.0199 ± 0.0259, +0.0079 ± 0.0061, –0.0078 ± 0.0060, and +0.0135 ± 0.0110 for V, $b-y$, m_1, and c_1, respectively. Errors quoted are standard errors of the mean. Because there is no direct means of comparing the Praesepe data of (Reglero & Fabregat 1991) to that of Olsen (1993, 1994), we will adopt the offsets from the Hyades comparison as representative of the Praesepe photometry. The cluster data were then adjusted to the system of Schuster & Nissen (1988) using the transformation relations derived by Olsen (1993). It should be emphasized in all cases over the color range of interest, $b-y$ between 0.39 and 0.59, the corrections are small and cannot be the source of the discrepancy. The cluster data are then processed through the metallicity calibration for G dwarfs as derived in Schuster & Nissen (1989), the calibration currently adopted in most photometric analyses. The resulting abundances, [Fe/H], are plotted in Fig. 1 as a function of $b-y$ for the Hyades (filled circles) and Praesepe (open circles). Observations of the same Hyades star from two different catalogs were treated as independent data and plotted as separate points.

For stars hotter than $b-y=0.47$, most stars scatter between [Fe/H] = 0 and +0.2, indicative of the expected supersolar metallicity for stars in these clusters. A more detailed analysis shows that there is weak evidence for a smooth color dependence in the abundances, starting at [Fe/H] = 0.0 for the bluest stars, the cooler F dwarfs, and rising above +0.13 at $b-y=0.46$. For stars redder than $b-y=0.47$, there is a systematic decline in the calculated [Fe/H], reaching a minimum between [Fe/H] = –0.2 and –0.3 at $b-y=$ 0.52 to 0.53, then rising rapidly toward +0.2 for stars at the cool limit of the calibration. The fact that the pattern is the same for two clusters of the same [Fe/H] observed independently by two different groups ensures that this is not a problem tied to a systematic error in the photometry.

Though the photometry itself may not be the issue, perhaps the clusters, both metal-rich and moderately young, suffer from some form of anomaly which distinguishes them from the typical field star of the same [Fe/H] and temperature. An example of such an effect which immediately comes to mind is the aptly named *Hyades anomaly* (e.g., Nissen 1988; Dobson 1990; Reglero et al. 1992; Joner & Taylor 1995). To test this possibility, we have processed the two primary, G-star *uvby* catalogs (Olsen 1993, 1994) through the same metallicity calibration, after applying adjustments for offsets relative to Schuster & Nissen (1988). The catalogs are treated separately because they emphasize different temperature ranges and are constructed using different selection criteria. The metallicity distribution as a function of color is illustrated for Olsen (1993) in Fig. 2a and for Olsen (1994) in Fig. 2b. Though the catalogs are not composed of a random sample of the cooler stars in the solar neighborhood due to biases imposed by the spectral classification selection and apparent magnitude limits, there is a broad range in [Fe/H] at all colors. The striking element common to both samples is the decline in the number of stars with [Fe/H] greater than 0.0 for $b-y$ greater than 0.49. The only difference of note in comparison with the cluster data is that the decline in the distribution is triggered at a marginally redder color than found with the clusters, a point we will return to in Sec. 4.

Though it appears that a problem exists within the G-star calibration, its source is less obvious. We emphasize that by the source of the discrepancy, we are not referring to the explicit reason why the error was included in the original calibration. It is a trivial point to assume that when a calibration of this type exhibits discrepancies, the origin of the error can be traced back to some combination of photometric errors, spectroscopic

abundance errors, or a sample size inadequate to cover the parameter space of interest. The sample used by Schuster & Nissen (1989) is no exception in that, despite the explicit statement that the abundance calibrations were appropriate between $b-y = 0.38$ and 0.59 up to [Fe/H] = +0.4, the sample is heavily weighted toward stars of halo metallicity.

By source of the discrepancy, we instead refer to the term(s) in the calibration relation that are inadequately or inappropriately sensitive to the changes in the stellar parameters, producing abundances that are not representative of the star. The rationale for this search is that it isn't enough to simply state that the abundances for some stars will be in error. If the errors are coupled to a specific photometric index, the size of the deviation may be coupled to a fundamental property of the star and lead to significant biases within samples chosen on the basis of photometry. Since the G-star calibration is being applied to extended samples for stellar populations studies, as discussed in Sec. 4, it is crucial to know which indices are primarily responsible for the discrepancy.

In the traditional approach to metallicity calibration with the *uvby* system, a metallicity index is derived by determining the difference between the observed m_1 index of a star and the value on a standard relation at the same temperature as defined by a color index such as $b-y$ or Hβ (Crawford 1975; Olsen 1984). The value of δm_1 is then transformed to [Fe/H] using some functional form which includes the potential secondary effects of temperature and surface gravity variation. Schuster & Nissen (1989) use the actual indices, $b-y$, m_1, and c_1, rather than differential terms, and an extensive set of polynomial dependences, including cross-terms among the different indices. Because of the extensive list of terms, some of which involve quadratics, the coefficients of each term can be large. The result is that the final value of [Fe/H] for a star is often obtained by taking differences among comparably large terms, the net sum of the small differentials resulting in an [Fe/H] value between +0.5 and –3.0. It must be emphasized that this approach should lead to a calibration as good as if not better than that developed by the simpler, traditional differential technique, and the tests of the final calibration by Schuster & Nissen (1989) seem to bear that out. ¿From the standpoint of a user, the one weakness of the calibration is the difficulty in deciding the degree to which variations among the different stellar parameters - temperature, surface gravity, and metallicity - influence the final photometric abundance through the various indices. Disentangling the effects of the various terms in the calibration will be the focus of next section.

3. The Source of the Anomaly

If there are weaknesses with the G-star calibration, one might assume that the need exists for a full-scale recalibration of the metallicity function over the entire cool star range at all [Fe/H]. Though clearly desirable, it isn't necessary for the purposes of this investigation and, in fact, is not be feasible with the spectroscopic sample available today. From the cluster data discussed above, the field star data of Fig. 2, and tests of the calibration from spectroscopic comparisons (e.g., Edvardsson et al. 1993), with minor modifications discussed below, the relation appears to work reasonably well for the hotter stars, i.e., $b-y$ less than 0.47, at all [Fe/H], though there is a modest color dependence to the zero point of the abundances even among the hotter stars. The issue is the source of the discrepancy among the stars in the cooler half of the calibration range, the late G and early K type stars with [Fe/H] approximately solar or higher. Despite a number of investigations of dwarf stars over the last decade, the number of cooler G and hotter K dwarfs of approximately solar abundance with spectroscopic abundance determinations remains scant; most surveys have concentrated on stars of lower metallicity within the old disk and/or halo, as did the original photometric study by Schuster & Nissen (1989). Moreover, in most spectroscopic studies, the number of stars surveyed remains small, leading to difficulties in ensuring that the abundances obtained from one analysis are on the same system as that of another. For this investigation, the best, internally consistent, spectroscopic sample of significant size for which *uvby* data are available comes from Favata et al. (1997).

Following the approach adopted in many of the recent studies, the 91 stars of Favata et al. (1997) were checked against the *uvby* catalog of Hauck & Mermilliod (1998), providing photometry for 35

stars between $b-y = 0.38$ and 0.60. This photometry was then adjusted to the system of Schuster & Nissen (1988) using the offsets of Olsen (1993) since the majority of the composite photometry is based upon the work of Olsen (1983, 1984, 1993, 1994). The sample of 35 stars was divided into 2 groups with a boundary at $b - y = 0.47$; 23 stars fell within the hotter regime while 12 defined the cool subset. The photometric abundances are plotted as a function of the spectroscopic values in Fig. 3, where the hotter stars are open squares and the cool stars are filled. The difference in slope between the two data samples is obvious. A linear fit for the hotter stars produces the relation $[Fe/H]_{phot} = 0.85\ [Fe/H]_{spec} + 0.02$, identical within the uncertainties with the trends found by Alonso et al. (1996) and Haywood (2001). In contrast, the 12 cooler dwarfs define a relation $[Fe/H]_{phot} = 0.39\ [Fe/H]_{spec} - 0.19$, with very small scatter. If the small sample of cooler dwarfs is representative of the general population, the sharp changes seen in the distributions of Figs. 1 and 2 are not merely the product of a flaw in the zero-point of the metallicity calibration with increasing color, but are due in large part to a serious error in the slope.

If there is a significant problem with the G-star calibration that goes beyond an issue with the zero point, the source of the error remains hidden within the functional form of the metallicity calibration. To gain some insight into which of the variables may hold the key, we plot in Fig. 4 the correlation of spectroscopic [Fe/H] (open stars) and photometric [Fe/H] (filled squares) with m_1 for the 12 cooler stars in Fig. 3. Other than the predictable fact that the photometric abundances cover a more modest range in [Fe/H], there is no significant difference between the patterns exhibited by the data as a function of m_1. There is also little correlation between [Fe/H] and m_1, implying that, other than increasing the scatter, random variations in m_1 are unlikely to propagate through the G-star calibration to produce the correlated deviations with [Fe/H] seen in Fig. 3. In Fig. 5, we repeat the same exercise for c_1. The difference is striking. For both abundance estimates, increasing [Fe/H] is highly correlated with increased c_1. In fact, for the photometric values, c_1 alone provides an excellent indicator of [Fe/H]. We emphasize that this trend is not an artifact of the small sample. We have repeated the exercise for the *uvby* catalogs of Olsen (1993, 1994) and find the same result for those samples, reflecting the result that the G-star calibration has a strong dependence on c_1, in contrast with the results for hotter dwarfs in the field (Crawford 1975; Schuster & Nissen 1989; Edvardsson et al. 1993) or in clusters with turnoffs in the F star range (Twarog 1983; Nissen et al. 1987; Anthony-Twarog & Twarog 1987). What Fig. 5 indicates is that the size of the dependence of [Fe/H] on changes in c_1 for the cooler star metallicity calibration is too small. If the spectroscopic abundances of Fig. 5 and the linear relations of Fig. 3 are correct, for cool dwarfs near solar abundance the variation of [Fe/H] with c_1 should be approximately doubled.

4. The Impact

Before discussing the specific role of the calibration error in solar neighborhood stellar analyses, a more general issue is the relevance of the G-star calibration within such studies. As noted earlier, the original intent of the Schuster & Nissen (1989) paper was heavily weighted toward stars of lower metallicity, and the long term history of the application of the F and G dwarf calibrations bears out this view. The use of the calibration for stars of solar metallicity would appear to be pushing the limits of the viability of the technique. Errors should be expected and have been noted in every study that has made extensive use of the calibration. The approach taken in refining the G-star calibration to adjust for these deficiencies has been virtually identical in every case and mimics the procedure used to revise the F-star calibration by Edvardsson et al. (1993), as illustrated by the technique used in the construction of Fig. 3. Abundances are derived for stars using the original G-star calibration and compared with the updated spectroscopic data for the same stars. A linear transformation is derived that permits the photometric abundances to be translated to the spectroscopic system.

Such internal checks have formed the appropriate basis justifying the use of the original G-star calibration in every major study of the last two years (Rocha-Pinto et al. 2000; Laughlin 2000; Haywood 2001; Feltzing et al. 2001), and each study has corroborated the conclusion

of the earlier work. With only a minor modification to the slope and/or zero point, the original G-dwarf metallicity calibration provides reliable relative metallicity estimates for stars over the entire color range and metallicity range. For stars near Hyades metallicity, the repeatedly calculated offset lies between 0.0 and +0.1 dex.

What Figs. 1 and 2, in conjunction with the analysis in Sec. 3, demonstrate is that no simple linear transformation or zero-point adjustment is capable of placing the stars within the G-dwarf range on an internally or externally correct metallicity scale. Moreover, the minor adjustments derived to date to modify the photometric abundances are totally inadequate. Though the hotter stars require offsets between 0.0 and +0.1 dex, the cooler half of the color range demands adjustments between +0.1 and +0.4 dex, the size of the offset being strongly dependent upon the color of the star. As with the original calibration, the failure to identify this problem lies with the dominance of the hotter dwarfs in the spectroscopic comparisons used to test and revise the calibration.

If the primary flaw in the G-star calibration lies with the c_1 dependence, how will this impact studies based in part upon a sample of such stars? Though the abundances of cooler stars will be systematically in error, the key question is whether or not the problem will affect all stars with equal severity. Unfortunately, the answer is no. The c_1 index for cooler stars has long been used as a means of separating dwarfs from giants and subgiants (Olsen 1984; Pilachowski et al. 1993; Anthony-Twarog & Twarog 1994), but these samples have involved stars of primarily halo and/or mixed [Fe/H]. To see the degree to which changes in luminosity alter the c_1 index at a fixed [Fe/H] comparable to the metallicity of the disk, we turn to the discussion of Twarog et al. (1999). This investigation includes an analysis of the distance to the LMC using the open cluster NGC 2420 as a link between the main sequence of the theoretical isochrones, as fixed by the solar neighborhood dwarfs (Twarog et al. 1999), and the LMC. The field stars with *Hipparcos* parallaxes were selected using the metallicity provided by the G-dwarf calibration under discussion and required to lie between [Fe/H] = –0.3 and –0.5, with an assumed cluster [Fe/H] of –0.4. By pure luck, the one region where the G-dwarf calibration overlaps with the spectroscopic in Fig. 3 is at [Fe/H] = –0.4, so the stars under consideration did, in the mean, have approximately the same [Fe/H] of –0.4. For the stars near $b - y = 0.5$, the c_1, $b - y$ diagram allowed perfect separation of subgiants at the base of the giant branch from unevolved main sequence stars of the same color. A difference of 0.06 in c_1 translated into a difference of over two magnitudes in M_V, a less dramatic effect by a factor of two to three than found among halo stars (Pilachowski et al. 1993; Anthony-Twarog & Twarog 1994), but readily detectable among disk field stars with precision photometry. Differences in c_1 significantly larger than this should imply a more evolved star, i.e., a giant, at a given color near solar [Fe/H].

Among cooler stars, two factors can generate significant changes in c_1. For unevolved stars at a given $b - y$, higher [Fe/H] leads to larger c_1. Second, at a given $b - y$, luminosity alters c_1 in that more evolved stars have larger c_1. The effect is not limited to subgiant versus dwarf; the c_1 index should also change as a star evolves away from the zero-age-main-sequence (ZAMS) with age. Though the latter effect is smaller, a modest evolutionary effect can mimic that of a metallicity change, and therein lies the problem. The weakness of the G-dwarf calibration is that it does not adjust the metallicity enough to account for the larger value of c_1 expected because of the higher [Fe/H]. However, if a star is significantly evolved away from the ZAMS, but still not a subgiant, the increased c_1 due to evolution could compensate for the inadequate size of the term in the calibration. Thus, one might expect that some metal-rich stars will be correctly identified as such as long as they are sufficiently evolved.

To test this possibility, we have run the catalogs of Olsen (1993, 1994) through the G-star calibration and selected those stars which have $[Fe/H]_{phot}$ greater than 0.10 and $b-y$ greater than 0.45, a horizontal cut through the Figs. 2a and 2b. These stars were matched with the *Hipparcos* parallax catalog (Perryman et al. 1997). Any star with σ_π/π less than 0.15 was adjusted for the Lutz-Kelker correction (Lutz & Kelker 1973; Koen 1992) and plotted on a CMD. It was assumed that the stars had no reddening. The result is shown in Fig. 6. Also shown is the main sequence for the Hyades using the composite sample constructed by Anthony-Twarog et al. (2002) and the abso-

lute magnitudes of Perryman et al. (1998). Stars that exhibit any indication of multiplicity from the summary by de Bruijne et al. (2001) have been excluded.

The single-star main sequence (filled circles) of the cluster is extremely tightly defined. In contrast, the field stars from Olsen (1993) (open triangles) and Olsen (1994) (squares) extend over a wide range in absolute magnitude with a remarkable cutoff at $b-y=0.485$. The number of stars between $b-y=0.49$ and 0.57 is small, with a modest number reappearing at $b-y=0.58$. This peculiar distribution is a reflection of the calibration problem noted in Fig. 1, coupled with the selection biases of the samples and the red limit of the subgiant branch. Stars that are Hyades metallicity or higher have photometric abundances that are systematically underestimated among the cool stars. Only at the red limit of the G-star metallicity calibration ($b-y \sim 0.58$) does this effect weaken due to the curvature seen in Fig. 2. However, what is more important from the standpoint of this discussion is the nature of the stars that are picked as being metal-rich.

As one moves down the main sequence toward cooler temperatures, the field star distribution reaches an approximate limit in M_V; few stars are found fainter than $M_V = 5.5$ until the cool limit of the sample is attained. This implies that between $b-y=0.45$ and 0.57, a star must be located in a CMD position increasingly above the unevolved/partially evolved main sequence of the Hyades. It is unlikely that the stars in this color range in Fig. 6 are located above the main sequence because they are binaries. Composites of two, almost identical, main sequence stars will shift the system about 0.7 mag above the main sequence, but will not significantly alter the color indices. Thus, a composite system will be affected by the photometric metallicity error to the same extent as a single star. The stars located between $b-y=0.47$ and 0.57 have survived the cut because of some combination of (a) very high metallicity, (b) evolution off the main sequence, and (c) photometric errors that scatter them into the high metallicity regime.

This point is clarified in Fig. 7, where the c_1, $b-y$ diagram for the stars in Fig. 6 is presented; the filled circles are the Hyades data of Olsen (1993, 1994) transferred to the same system as the field stars. Note that the scatter in Hyades c_1 is the primary source of the [Fe/H] scatter in Fig. 1. It is apparent that the two-color diagram is a reflection of the the CMD; the M_V cut in Fig. 6 is translated into a diagonal cut in the $c_1, b-y$ diagram, an effect which disappears at the cool limit of the sample. What is surprising is the set of c_1 values for the seven stars between $b-y=0.5$ and 0.55. Despite the fact that these stars are positioned only 0.2 to 0.7 mag above the Hyades relation in the CMD, implying that they are not subgiants but main sequence stars, their c_1 indices place them 0.08 to 0.15 mag above the Hyades relation, classifying them photometrically as giants. Since they are not significantly evolved and the size of the difference in c_1 is too large to be caused by photometric error, either these stars suffer from some form of atmospheric anomaly that distorts their indices, or they are very metal rich.

The seven extreme stars are HD 7199, 24257, 77712, 87000, 100508, 122640, and 145675. Perhaps the most studied of these is HD 145675 (14 Her). This star has been the focus of a good deal of attention because of the discovery of planets around the system (Mayor et al. 1999), as well as confirmed, spectroscopic abundances that classify the star as super-metal-rich, with [Fe/H] above +0.3 (Taylor 1996; Gonzalez et al. 1999). Its virtual twin, HD 75732, occupies the same areas of the CMD and the color-color diagram, but missed the cut in [Fe/H] because its photometric abundance is +0.09. For the remaining six stars, no additional information is available which might cast some light on their location in these figures. If HD 145675 is typical of this select group, its location in the CMD well above the Hyades main sequence is a consequence of some combination of the shift in the ZAMS to higher M_V at a given $b-y$ due to an increase in [Fe/H] of between 0.3 and 0.4 dex relative to the Hyades and a greater degree of evolution. The increasing gap between the Hyades main sequence and the field stars starting at $b-y=0.47$ is likely to be a product of the growing discrepancy between the photometric and true abundance toward redder color, requiring an even higher intrinsic [Fe/H] and/or greater degree of evolution to meet the fixed cut in the photometric [Fe/H].

The luminosity effect on c_1 and, indirectly, on [Fe/H], provides a natural explanation for the

bluer break point in the distribution for the cluster stars compared with the field (see Figs. 1 and 2). The cluster stars at a given color are in the same evolutionary state and only moderately metal rich. The field star sample includes stars significantly more metal rich than the Hyades, thus redder at a given temperature, and covering a range in evolutionary state from the unevolved main sequence to subgiants at the same color.

An approximate estimate of the significance of the calibration distortion on a sample selected for purposes of stellar population analysis may be obtained in the following way. For the Hyades stars with *uvby* photometry as plotted in Fig. 1, a mean photometric [Fe/H] has been derived as a function of $b-y$ between 0.39 and 0.57. Assuming the error in the photometric abundance is purely a zero-point error in the calibration, an offset can be calculated as a function of $b-y$ to bring the mean photometric abundance in line with that adopted for the cluster as a whole, in this case, [Fe/H] = +0.125. This color-dependent offset is then applied to any star processed through the calibration. Since we have already demonstrated that the error lies in a combination of both the slope and zero-point of the calibration (see Fig. 3), this crude fix will only give a reasonable adjustment to stars more metal-rich than the Hyades, with the uncertainty increasing for more metal-rich stars.

The resulting metallicity histogram for stars from the catalogs of Olsen (1993, 1994) with photometric [Fe/H] above +0.2, higher than the adopted Hyades value of +0.125, is shown in Fig. 8, where the solid line is the distribution based upon the corrected [Fe/H] and the dashed line is the distribution based upon the uncorrected G-star calibration of (Schuster & Nissen 1989). Such a sample would be appropriate in a search for metal-rich dwarfs to study as potential sources of planets, as exemplified by Laughlin (2000). We emphasize that no attempt has been made to remove spectroscopically peculiar stars, binaries, or spectroscopic giants in either sample. Our primary concern is the differential effect of the adjustment which clearly expands the sample of very metal-rich stars in both number and range. Moreover, the boundary of [Fe/H] = +0.2 is arbitrary; one could lower this to –0.1 and the pattern would remain the same. The source of the enhancement is shown in Fig. 9, where the samples of Fig. 8 are sorted by color. Superposed upon the bias in the original catalogs, which produces a decline in the number of stars redder than $b-y=0.50$, the metallicity adjustment leads to a significant number of high-metallicity stars at all colors, with the greatest enhancement at the red end of the distribution. Part of the decline in numbers at redder colors in both samples can also be attributed to the cool limit of the subgiant branch at higher [Fe/H]. Stars at the base of the giant branch will be selectively enhanced in number because they can be observed over a greater range in distance and because of potential effects on c_1 caused by evolution rather than metallicity.

5. Summary and Conclusions

Field star *uvby* data from the high precision, photometric catalogs of Olsen (1993, 1994) and cluster photometry for the Hyades and Praesepe have been analyzed to test potential issues involving the G-star metallicity calibration of Schuster & Nissen (1989). The reliability of the photometric approach has taken on increasing importance in bridging the gap between the extensive sample of stars with reliable kinematic and distance information and the small to modest number with consistent abundance estimates.

The field star and cluster data tell the same story: for dwarf stars of mid-G to early K, the metallicity calibration systematically underestimates the metallicity of the more metal-rich stars in the solar neighborhood, with the size of the discrepancy increasing toward higher [Fe/H]. Among the hotter half of the sample, the linear relation between photometric and spectroscopic abundances is similar to what has been found in earlier analyses (Alonso et al. 1996; Haywood 2001), but the cooler stars generate a linear relation that has half the slope of the hotter stars (see Fig. 3). It must be kept in mind at all times that while the reality of the discrepancy is obvious, the sample of stars that define the change in the linear relations is small. It should not be assumed that the problem can be corrected by simply subdividing stars into two color groups. The required adjustments may depend upon the slope, the zero-point, or both, and the relative contribution of either parameter may vary with $b-y$.

The source of the problem appears to lie with

the metallicity dependence of the c_1 index. The reason for its long-standing survival in the calibration is best illustrated by comparison with the *uvby* metallicity calibration for F stars. The most commonly adopted calibrations for the hotter dwarfs are those of Crawford (1975) and Schuster & Nissen (1989), modified in a modest way by Edvardsson et al. (1993). The F-dwarfs were a focus of the early work on age determination among solar neighborhood stars because they had the greatest potential for exhibiting large deviations from the ZAMS in an age range comparable to the lifetime of the disk, an important property given the need for precise determination of absolute luminosity from photometric or trigonometric methods. Thus, the sample of stars with available spectroscopic data in this temperature regime grew in response to the need to define the stellar abundances reliably, culminating in the extensive sample of Edvardsson et al. (1993). Other than modest adjustments introduced by changes in the spectroscopic abundance scale, the F-star calibrations have remained quite stable with excellent agreement among the various investigators. Repeated cross-checks with expanded samples have made errors of the type noted above difficult to sustain.

The second, more critical factor has been the availability of cluster photometry on the *uvby* system. F-stars in a number of nearby open clusters were well within reach of traditional, photoelectric photometers and the changeover to CCD's has expanded this option to even greater distance. While permitting a check on the metallicity calibrations via the chemically well-defined sample within a cluster, clusters of intermediate and older age gave direct tests of the impact of main sequence evolution on the metallicity calibration and the relationship between δc_1 and δM_V. Repeated observations of a large sample of clusters (e.g., Crawford & Barnes 1970; Nissen et al. 1987; Anthony-Twarog & Twarog 1987; Schuster & Nissen 1988; Daniel et al. 1994) have confirmed the conclusion from field star data that the F-star m_1 metallicity calibration has little to no dependence on c_1. It must be emphasized that there is, at present, no evidence for any systematic difference between spectroscopic and photometric *uvby* abundances for F-stars in the field or in clusters beyond those required by ongoing revisions in the spectroscopic scale.

In contrast, while the spectroscopic sample of G-dwarf abundances, particularly at solar metallicity and above is growing, it still remains modest and not always internally consistent. Though CCD photometry now places such observations within reach, the number of open clusters where the cool G and K-dwarf members have been observed on the *uvby* system remains limited to a few nearby open clusters (Reglero & Fabregat 1991; Reglero et al. 1992). The combination of these two factors is critical because the implication of our analysis is that, contrary to what is found for the hotter stars, the c_1 index for cooler dwarfs is strongly affected by variations in [Fe/H]. The rapid rise in sensitivity occurs near $b - y = 0.47$, making more metal-rich dwarfs appear more evolved, i.e., have a higher c_1 index. The effect is so extreme that main sequence stars with metallicity well above the Hyades value are photometrically classified as giants, a secondary source of problems because the transformation between instrumental and standard indices for cooler stars is often dependent upon the luminosity classification of the star, as illustrated by the *Caby* transformation in Twarog & Anthony-Twarog (1995). The absence of an extensive sample of cool dwarfs with spectroscopically determined abundances at all [Fe/H] covering varying degrees of evolution, particularly at the metal-rich, cooler end of the distribution, makes adequate determination of the impact of the metallicity effect on c_1 difficult, if not impossible. The plausibility of the color effect illustrated in Fig. 3 rests primarily upon its consistency with the unmistakable distortions of Figs. 1 and 2.

The effect of the calibration error in the *uvby* system on abundance determination is straightforward, but caution is recommended in interpreting its impact on stellar population studies. Cool dwarfs of solar metallicity and above will have their abundances underestimated by a significant amount and many metal-rich dwarfs will be incorrectly excluded from study because they are photometrically classed as giants. However, metal-rich stars that are well-evolved off the main sequence or located in the subgiant region will see some partial correction to their photometric abundances due to evolutionary effects on c_1. The result could be that truly metal-rich evolved stars

will be preferentially selected in surveys for metal-rich stars, while their unevolved counterparts are excluded. Since the evolutionary effect only partially corrects for the photometric underabundance, stars with parallaxes will find themselves positioned even farther above a ZAMS defined by their lower, photometric [Fe/H], leading to an excessively large age determination for stars already selected because they are, on average, older. Until a reliable means of disentangling the influence of luminosity and metallicity effects on c_1 indices is obtained, photometric *uvby* abundances for cooler field stars, and stellar population analyses tied to them, should be regarded with skepticism.

The authors gratefully acknowledge the thoughtful comments and suggestions of the referee, Dr. Ken Yoss, which made the publication of this paper possible.

REFERENCES

Alonso, A., Arribas, S., & Martinez-Rogers, C. 1996, A&AS, 117, 227

Anthony-Twarog, B. J., Laird, J. B., Payne, D., & Twarog, B. A. 1991, AJ, 101, 1902

Anthony-Twarog, B. J., Sarajedini, A., Twarog, B. A., & Beers, T. C. 2000, AJ, 119, 2882

Anthony-Twarog, B. J., Shawl, S. J., & Twarog, B. A. 1992, AJ, 104, 2229

Anthony-Twarog, B. J., & Twarog, B. A. 1987, AJ, 94, 1222

Anthony-Twarog, B. J., & Twarog, B. A. 1994, AJ, 107, 1577

Anthony-Twarog, B. J., & Twarog, B. A., 1998, AJ, 116, 1902

Anthony-Twarog, B. J., Twarog, B. A., & Craig, J. 1995, PASP, 107, 32

Anthony-Twarog, B. J., Twarog, B. A, & Yu, J. 2002, AJ, in press

Baird, S. R. 1996, AJ, 112, 2132

Boesgaard, A. M. 1989, ApJ, 336, 798

Cayrel de Strobel, G., Soubiran, C., & Ralite, N. 2001, A&A, 373, 159

Crawford, D. L. 1975, AJ, 80, 955

Crawford, D. L., & Barnes, J. V. 1970, AJ, 75, 946

de Bruijne, J. H. J., Hoogerwerf, R., & de Zeeuw, P. T. 2001, A&A, 367, 111

Daniel, S. A., Latham, D. W., Mathieu, R. D., & Twarog, B. A. 1994, PASP, 106, 281

Dobson, A. K. 1990, PASP, 102, 88

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101

Favata, F., Micela, G., & Sciortino, S. 1997, A&A, 323, 809

Feltzing, S., Holmberg, J., & Hurley, J. R. 2001, MNRAS, in press

Friel, E. D., & Boesgaard, A. M. 1992, ApJ, 387, 170

Gonzalez, G., Wallerstein, G., & Saar, H. 1999, ApJ, 511, L111

Hauck, B., & Mermilliod, M. 1998, A&AS, 129, 431

Haywood, M. 2001, MNRAS, 325, 1365

Hintz, M. L., Joner, M. D., & Hintz, E. G. 1998, AJ, 116, 2993

Houk, N. 1978, Michigan Catalog of Two Dimensional Spectral Types for the HD Stars, Vol. 2 (Ann Arbor: Univ. Michigan)

Houk, N. 1982, Michigan Catalog of Two Dimensional Spectral Types for the HD Stars, Vol. 3 (Ann Arbor: Univ. Michigan)

Houk, N., & Cowley, A. P. 1975, Michigan Catalog of Two Dimensional Spectral Types for the HD Stars, Vol. 1 (Ann Arbor: Univ. Michigan)

Houk, N., & Smith-Moore, M. 1988, Michigan Catalog of Two Dimensional Spectral Types for the HD Stars, Vol. 4 (Ann Arbor: Univ. Michigan)

Houk, N., & Swift, C. 1999, Michigan Catalog of Two Dimensional Spectral Types for the HD Stars, Vol. 5 (Ann Arbor: Univ. Michigan)

Joner, M. D., & Taylor, B. J. 1995, PASP, 107, 124

Koen, C. 1992, MNRAS, 256, 65

Laughlin, G. 2000, ApJ, 545, 1064

Lutz, T. E., & Kelker, D. H. 1973, PASP, 85, 573

Mayor, M., Beuzit, J. L., Mariotti, J. M., Naef, D., Perrier, C., Queloz, D., & Sivan, J. P. 1999, in ASP Conf. Ser., IAU Colloq. 170, Precise Stellar Radial Velocities, ed. J. B. Hearnshaw & C. D. Scarfe (San Francisco; ASP)

Meusinger, H., Reimann, H. -C., & Stecklum, B. 1991, A&A, 245, 57

Nissen, P. E. 1988, A&A, 199, 146

Nissen, P. E., Twarog, B. A., & Crawford, D. L. 1987, AJ, 93, 634

Olsen, E. H. 1983, A&AS, 54, 55

Olsen, E. H. 1984, A&AS, 57, 443

Olsen, E. H. 1993, A&AS, 102, 89

Olsen, E. H. 1994, A&AS, 106, 257

Perryman, M. A. C., et al. 1997, A&A, 323, 49

Perryman, M. A. C., Brown, A. G. A., Lebreton, Y., Gomez, A., Turon, C., Cayrel de Strobel, G., Mermilliod, J. -C., Robichon, N., Kovalevsky, J., & Crifo, F. 1998, A&A, 331, 81

Pilachowski, C. A., Sneden, C., & Booth, J. 1993, ApJ, 407, 699

Reid, I. N. 2002, PASP, in press, astro-ph/0112402

Reglero, V., & Fabregat, J. 1991, A&AS, 90, 25

Reglero, V., Fabregat, J., Suso, J. 1992, A&AS, 92, 565

Rey, S. -C., Lee, Y. -W., Joo, J. -M., Walker, A., & Baird, S. 2000, AJ, 119, 1824

Rocha-Pinto, H. J., Maciel, W. J., Scalo, J., & Flynn, C. 2000, A&A, 358, 850

Schuster, W. J., & Nissen, P. E. 1988, A&AS, 73, 225

Schuster, W. J., & Nissen, P. E. 1989, A&A, 221, 65

Schuster, W. J., Parrao, L., & Contreras Martinez, M. E. 1993, A&AS, 97, 951

Soon, W. H., Zhang, Q., Baliunas, S. L., Kurucz, R. L. 1993, 416, 787

Taylor, B. J. 1996, ApJS, 102, 105

Twarog, B. A. 1980, ApJ, 242, 242

Twarog, B. A. 1983, ApJ, 267, 207

Twarog, B. A., & Anthony-Twarog, B. J. 1995, AJ, 109, 2828

Twarog, B. A., Anthony-Twarog, B. J., & Bricker, A. R. 1999, AJ, 117, 1816

Twarog, B. A., Ashman, K. M., & Anthony-Twarog, 1997, AJ, 114, 2556

This 2-column preprint was prepared with the AAS LATEX macros v5.0.

Fig. 1.— The metallicity of the Hyades (filled symbols) and Praesepe (open symbols) as a function of color using the *uvby* G-star calibration of Schuster & Nissen (1989).

Fig. 2.— The metallicity distribution as a function of $b-y$ for stars in the catalog of Olsen (1993) (a) and in Olsen (1994) (b) using the G-star calibration of Schuster & Nissen (1989).

Fig. 3.— Comparison of photometric and spectroscopic abundances for stars with $b-y$ less than 0.48 (open symbols) and those redder than $b-y=$ 0.48 (filled symbols). Dashed relation shows the linear fit to the hotter stars, the solid line the relation for the cooler stars.

Fig. 4.— Spectroscopic (open stars) and photometric (filled squares) abundances as a function of m_1 for the 12 cool stars of Fig. 3.

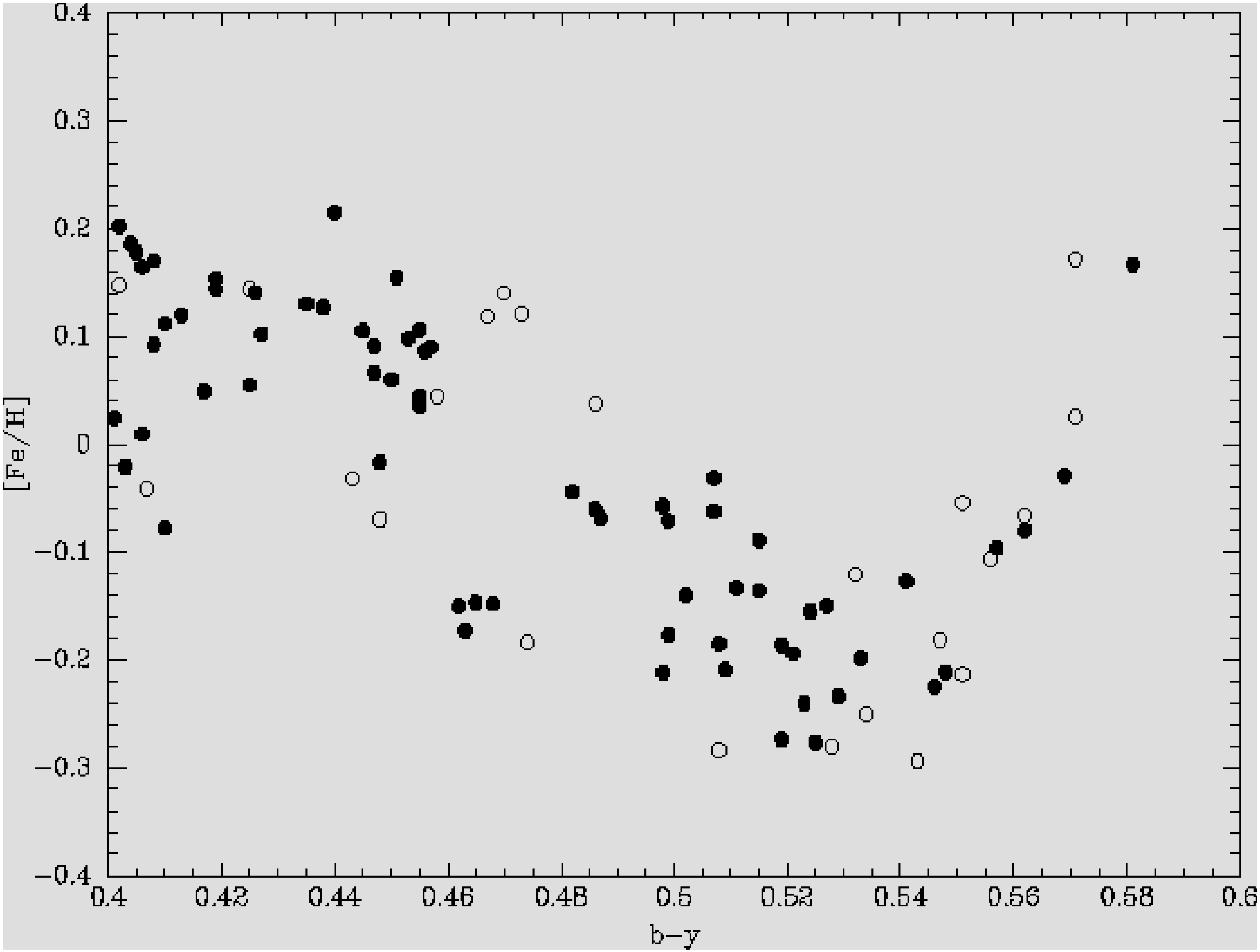
Fig. 5.— Same as Fig. 4 versus c_1.

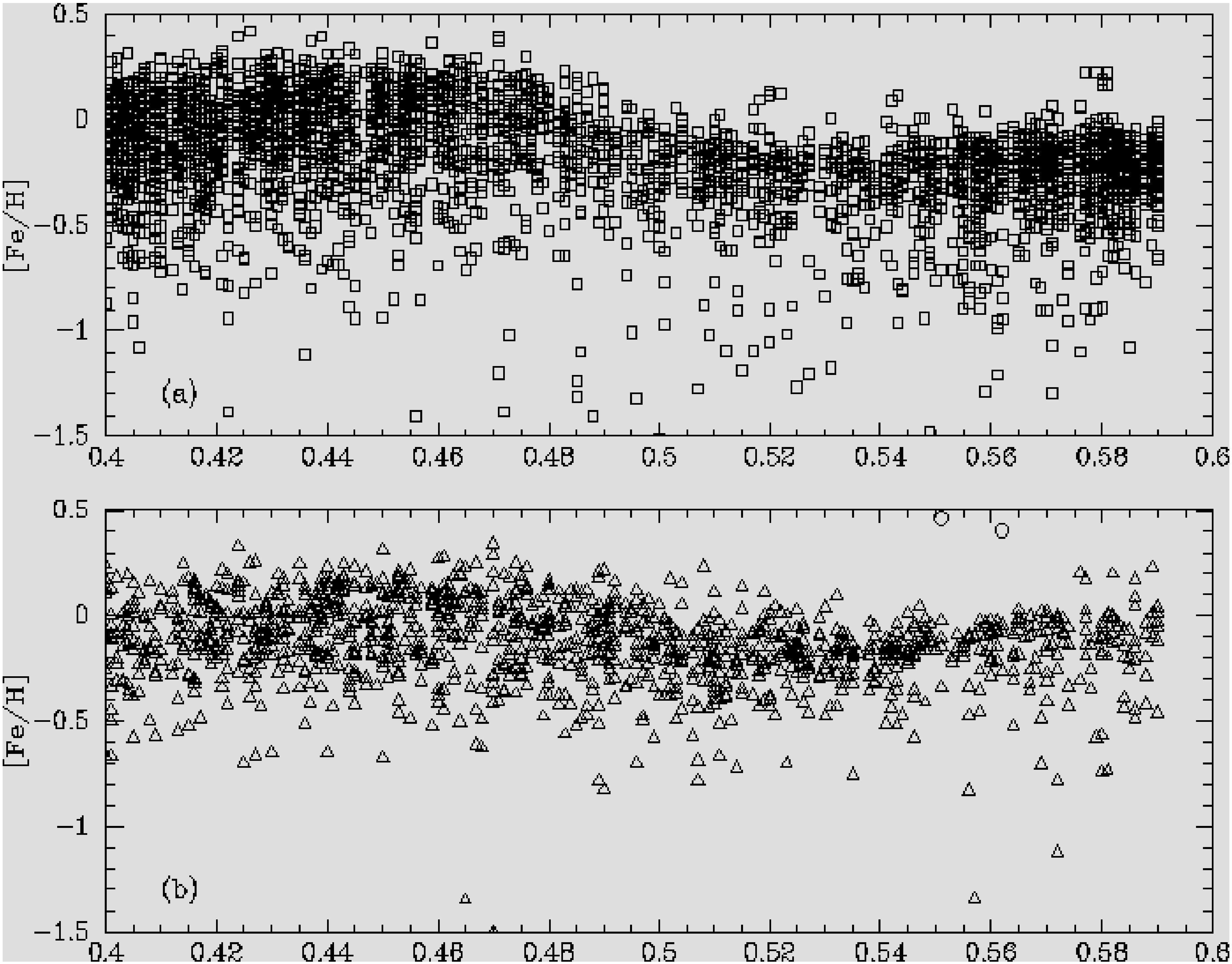
Fig. 6.— CMD for field stars with reliable parallaxes and photometric abundances greater than +0.10. Open squares are stars from Olsen (1993), open triangles are from Olsen (1994), and filled circles are Hyades stars.

Fig. 7.— Color-color plot for same stars in Fig. 6.

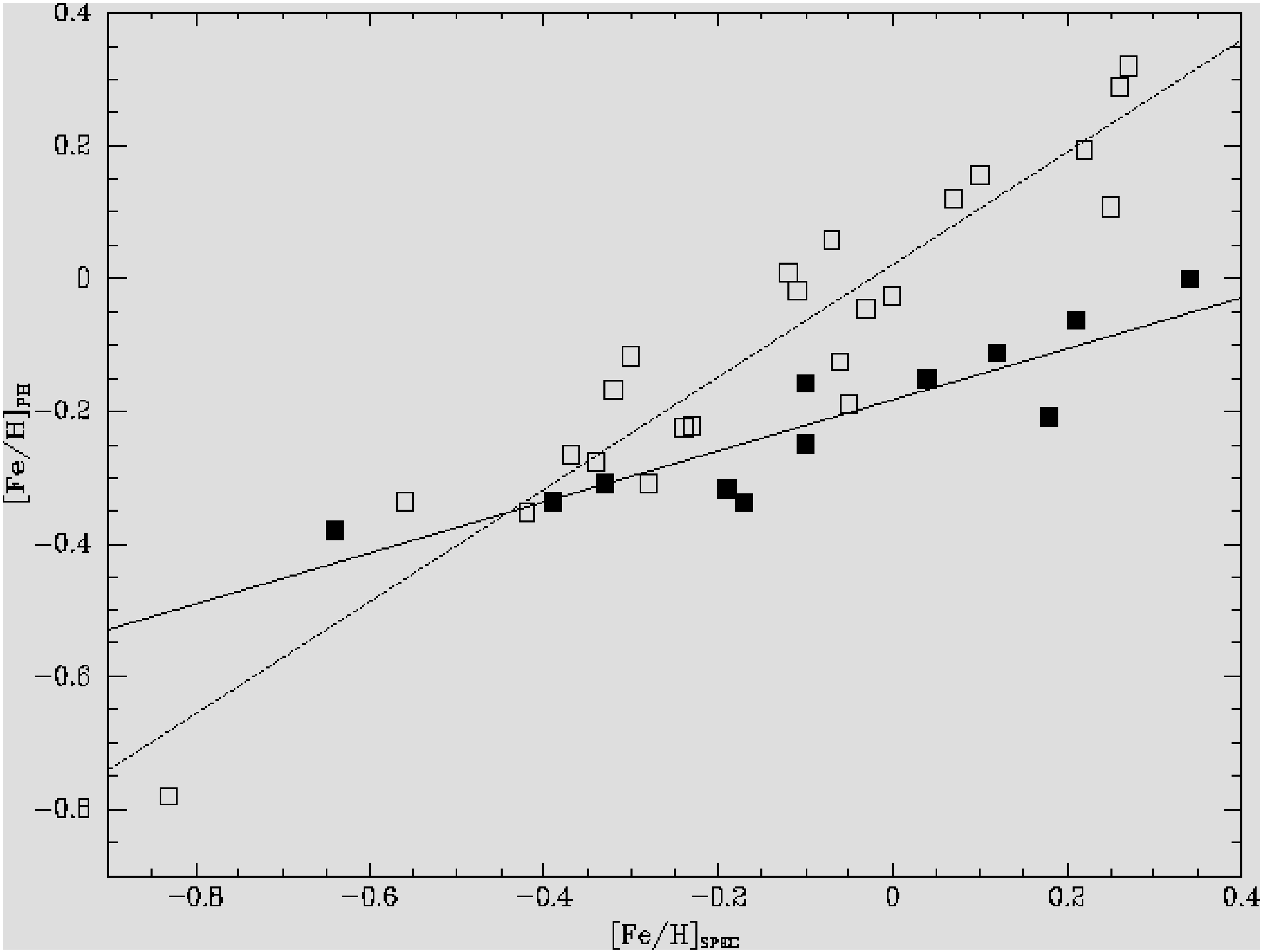
Fig. 8.— Distribution of photometric abundances for stars from Olsen (1993, 1994) between $b-y$ = 0.39 and 0.57 with [Fe/H] above +0.2. Dashed line refers to the original *uvby* calibration while the solid curve includes the adjusted abundances.

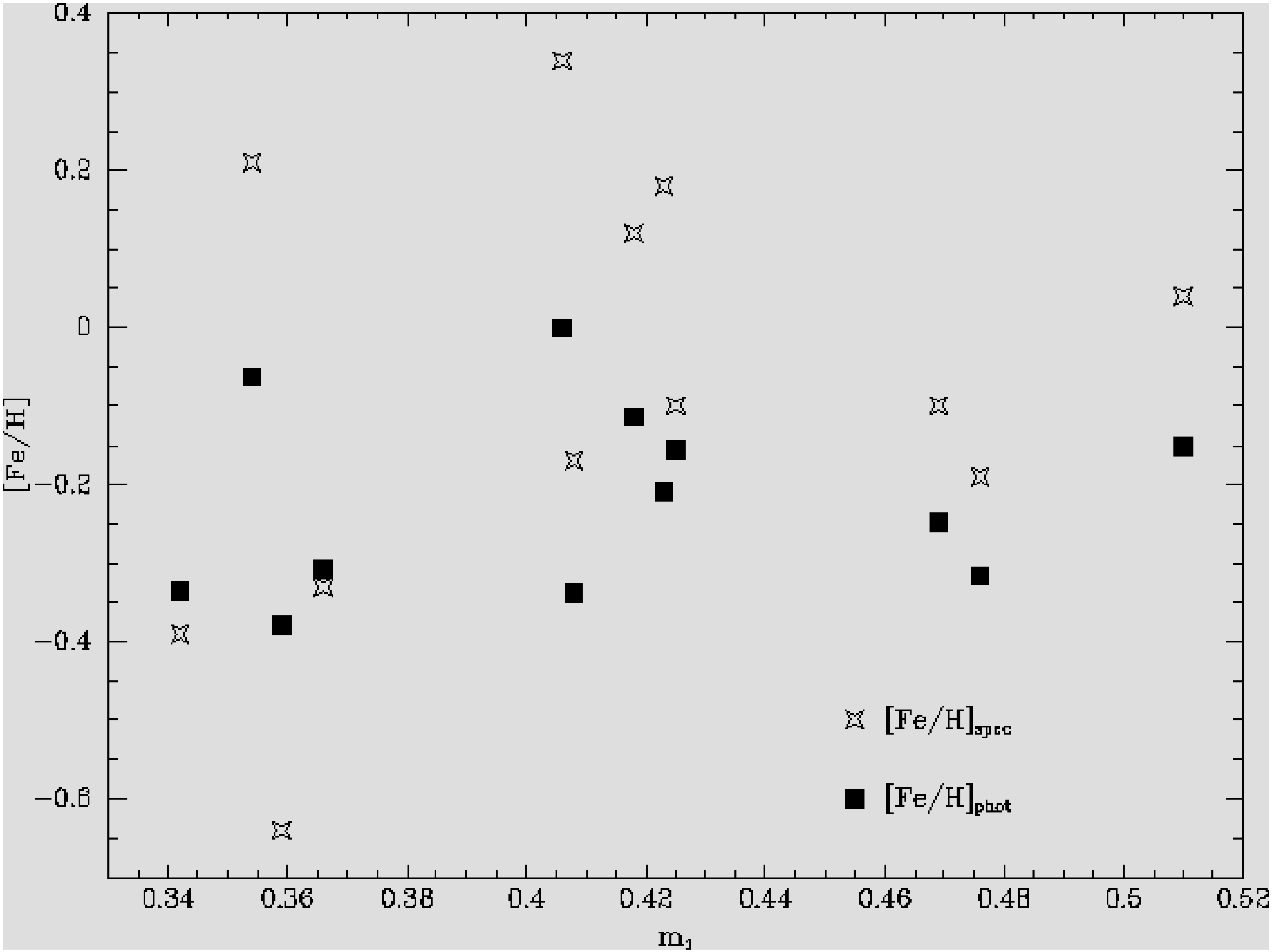
Fig. 9.— Distribution of abundances as a function of color for the same samples found in Fig. 8.


[Fe/H]
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
b−y

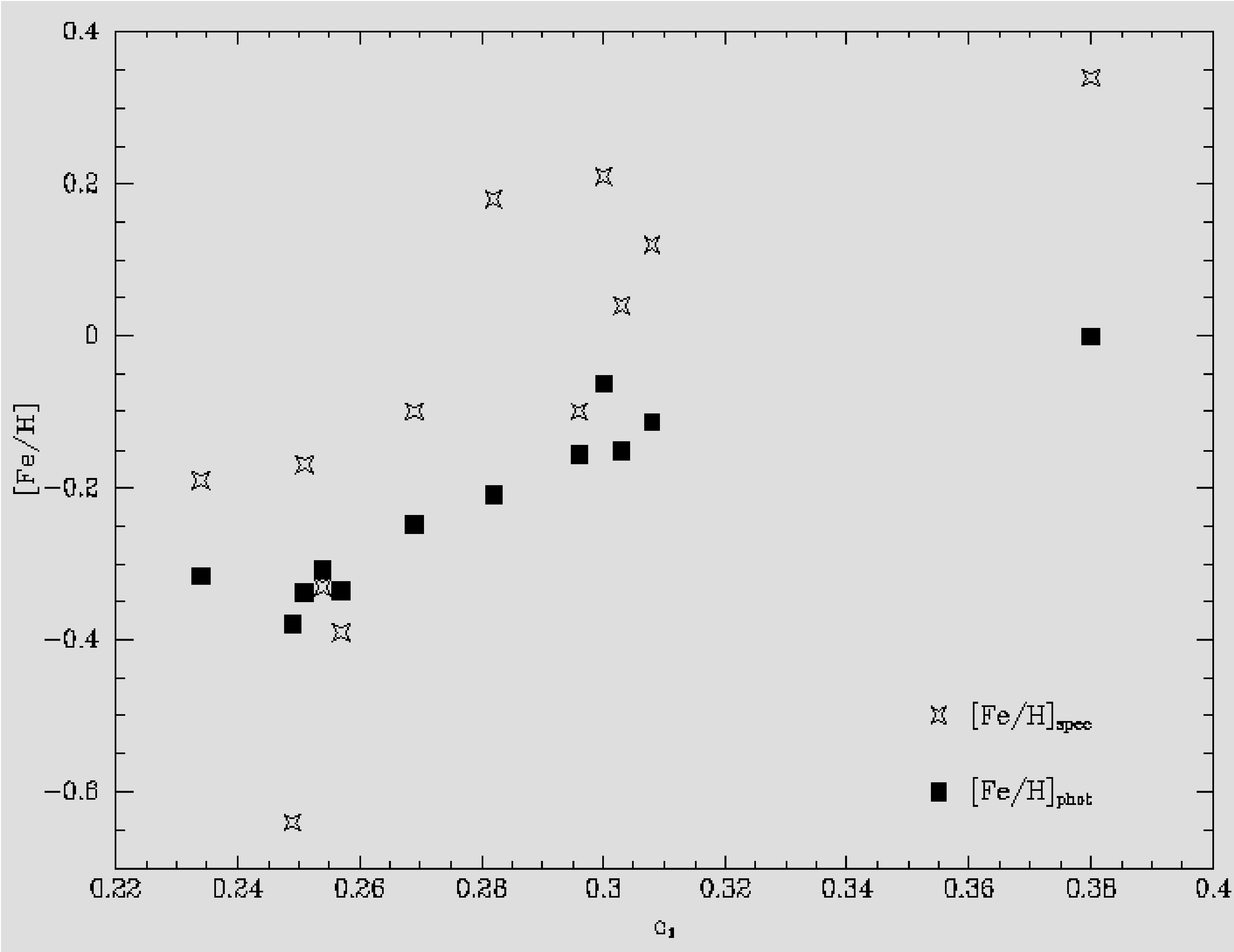


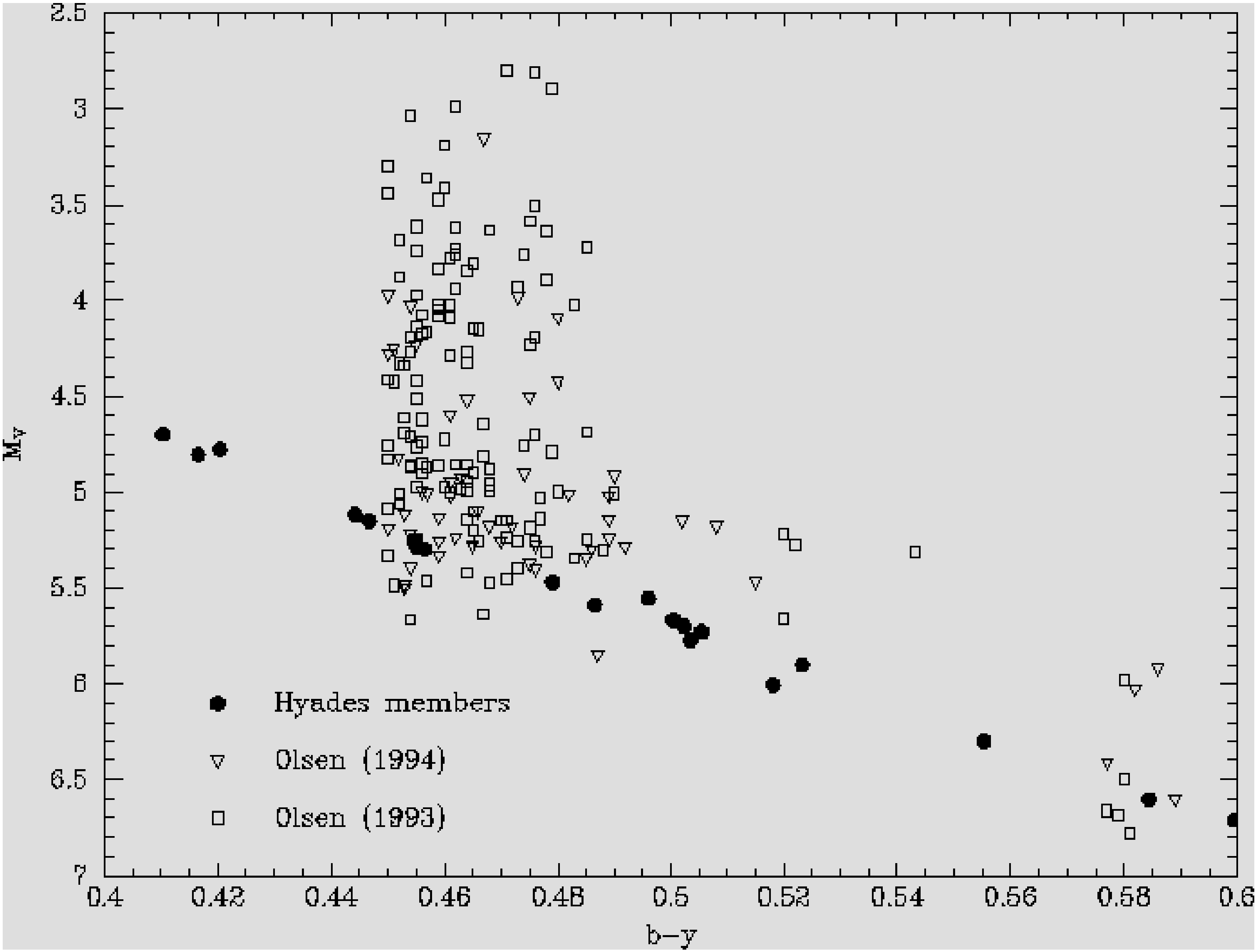
[Fe/H]
(a)
(b)


0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
[Fe/H]PH
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
[Fe/H]SPEC

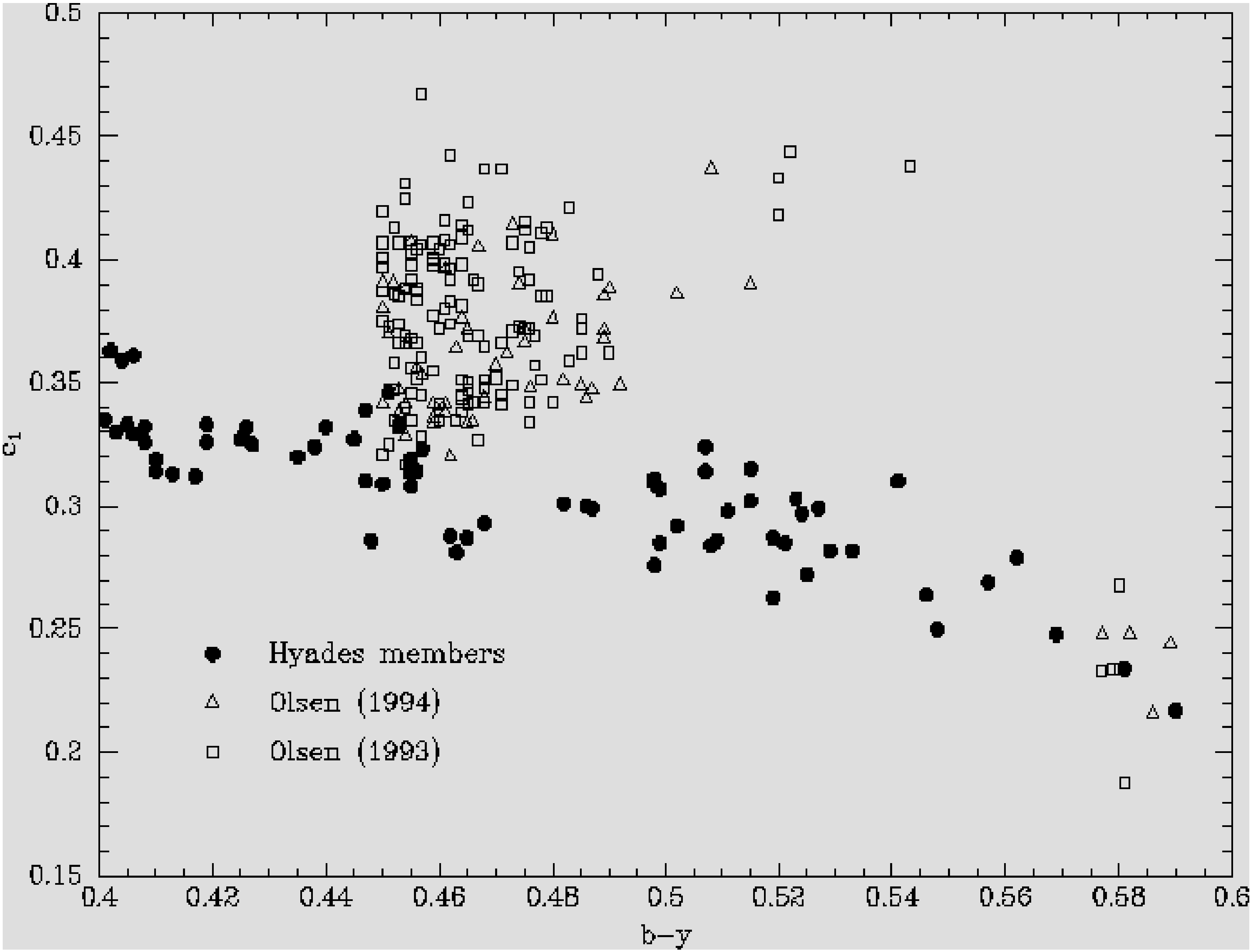


0.4
0.2
0
−0.2
−0.4
−0.6
[Fe/H]
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
m_1
$[Fe/H]_{spec}$
$[Fe/H]_{phot}$

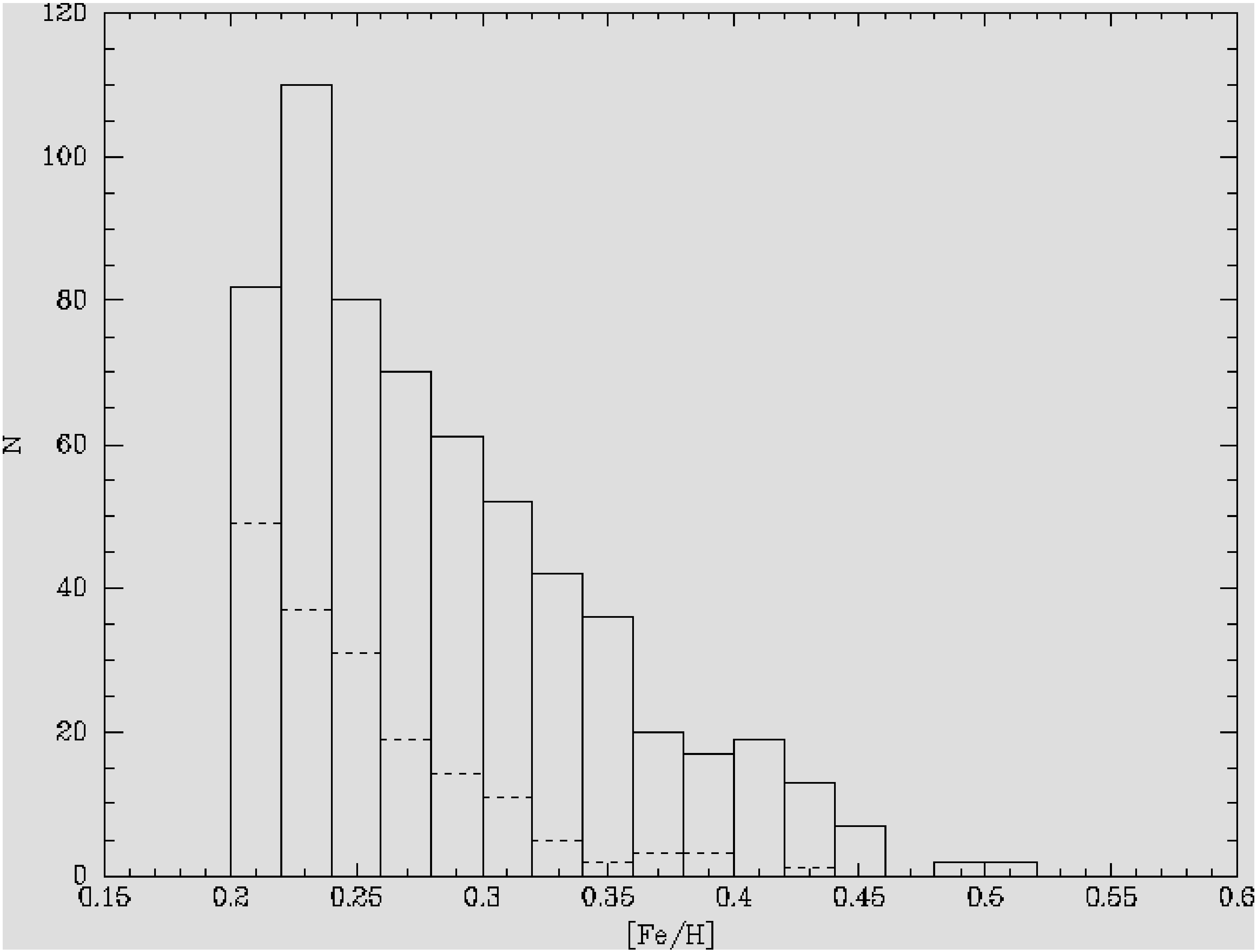

0.4
0.2
0
−0.2
−0.4
−0.6
[Fe/H]
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
c_1
$[Fe/H]_{spec}$
$[Fe/H]_{phot}$



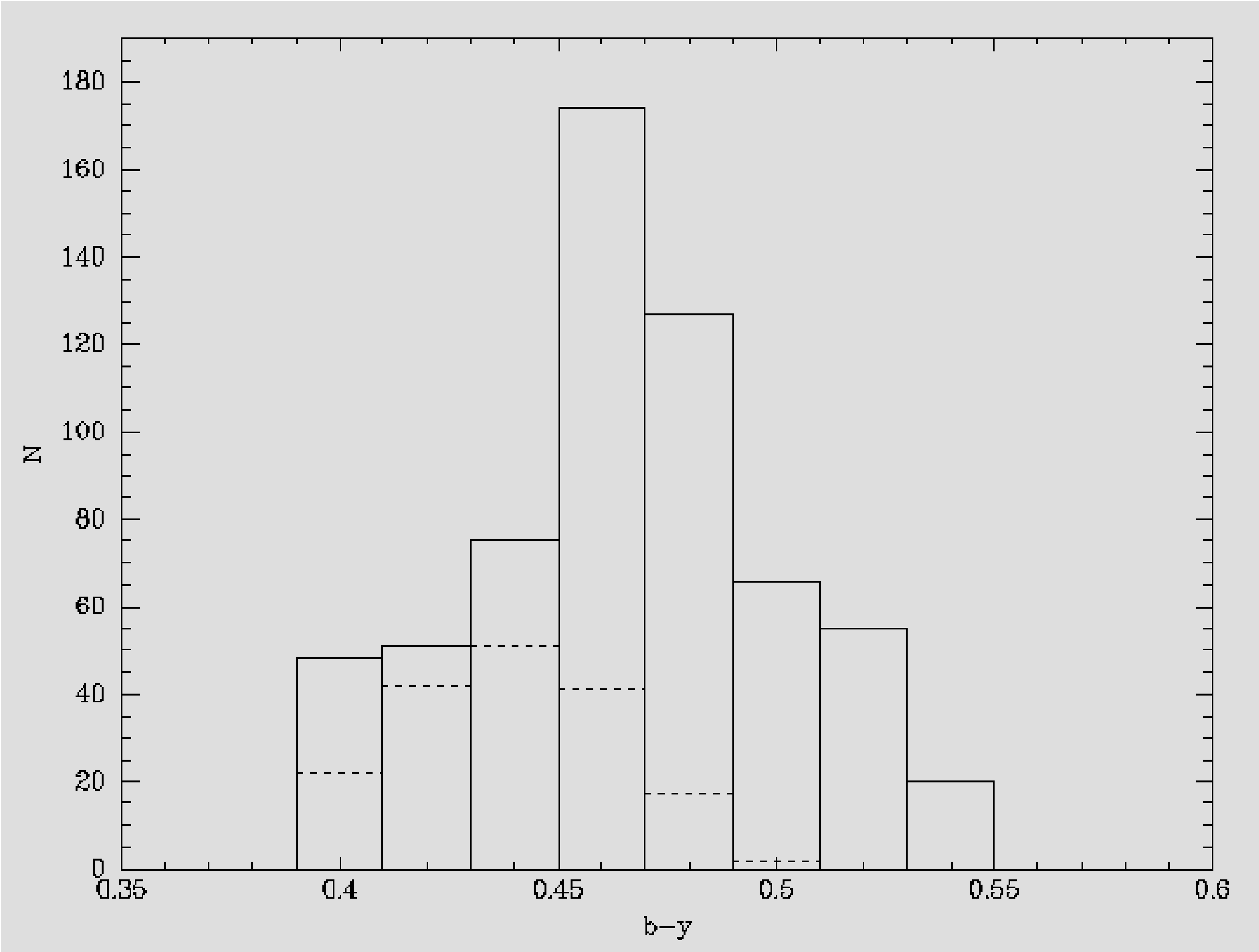
Hyades members
Olsen (1994)
Olsen (1993)
M_V
b−y



Hyades members
Olsen (1994)
Olsen (1993)
b−y
c1



120
100
80
60
40
20
0
N
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
[Fe/H]


N
180
160
140
120
100
80
60
40
20
0
0.35
0.4
0.45
0.5
0.55
0.6
b−y